HEAT EXCHANGER HAVING VARIABLE THICKNESS TIE RODS AND METHOD OF FABRICATION THEREOF

BACKGROUND

To improve the overall efficiency of a gas turbine engine, a heat exchanger or recuperator can be used to provide heated air for the turbine intake. The heat exchanger operates to transfer heat from the hot exhaust of the turbine engine to the compressed air being drawn into the turbine. As such, the turbine saves fuel it would otherwise expend raising the temperature of the intake air to the combustion temperature.

The heat of the exhaust is transferred by ducting the hot exhaust gases past the cooler intake air. Typically, the exhaust gas and the intake air ducting share multiple common walls, or other structures, which allow the heat to transfer between the two gases (or fluids depending on the specific application). That is, as the exhaust gases pass through the ducts, they heat the common walls, which in turn heat the intake air passing on the other side of the walls. Generally, the greater the surface areas of the common walls, the more heat which will transfer between the exhaust and the intake air. Also, the more heat which is transferred between the exhaust and the air, the greater the efficiency of the heat exchanger.

As shown in the cross-sectional view of Fig. 1a, one example of this type of device is a heat exchanger 5, which uses a shell 10 to contain and direct the exhaust gases, and a core 20, placed within the shell 10, to contain and direct the intake air. As can be seen, the core 20 is constructed of a stack 26 of thin plates 22 which alternatively channel the inlet air and the exhaust gases through the core 20. That is, the layers 24 of the core 20 alternate between channeling the inlet air and channeling the exhaust gases. In so doing, the ducting keeps the air and exhaust gases from mixing with one another. Generally, to maximize the total heat transfer surface area

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of the core 20, many closely spaced plates 22 are used to define a multitude of layers 24. Further, each plate 22 is very thin and made of a material with good mechanical and heat conducting properties. Keeping the plates 22 thin assists in the heat transfer between the hot exhaust gases and the colder inlet air.

Typically, during construction of such a heat exchanger 5, the plates 22 are positioned on top of one another and then compressed to form the stack 26. Since the plates 22 can separate if not held together, the compression of the plates 22 ensures that there are always positive compressive forces on the core 20 to hold the plates 22 in place. The separation of one or more plates 22 can lead to a performance reduction, or even a failure by a buckling of the stack 26. As such, the heat exchanger 5 is typically constructed with the stack 26 under a compressive pre-load.

Applying a high pre-load to the stack 26 reduces the potential for separation of the plates 22. However, to be able to apply pre-loads to the stack 26, a pre-load assembly or support structure 50 positioned about the stack 26, is needed. In addition to applying the pre-load to the stack 26, the support structure 50 carries any additional loading exerted by the stack 26. Such additional loads can come from a variety of sources, including thermal expansion of the stack 26 and the pressurization of air (or other medium) in the stack 26. Since the total loads applied to the support structure 50 can be relatively high, the support structure 50 can on occasion fail.

The support structure 50 collectively includes strongbacks 40, tie rods 30, and the shell 10 structure. The tie rods 30 are held to the strongbacks 40 by fasteners 36 positioned at the ends 32 of the tie rods 30. A single tie rod 30 is set forth in a side view in Fig. 1b and cross-section in Fig. 1c. The tie rod 30 has a center section 31. As can be seen, the tie rod 30 has a uniform thickness, T_r, along its entire length, as well as a rounded cross-section. As shown in the cross-section of Fig. 1d, the tie rod 30 has threads 34. The threads 34 have an inner diameter, D_{ri}, and an outer diameter, D_{ro}. The threads 34 receive the threads 38 of the fastener 36, such that the strongback 40 can be held in place by the tie rod 30.

The support structure 50, shown in Fig. 1a, adds to both the weight and the cost of the heat exchanger 5. Because the support structure 50 supports the core 20 (namely the stack 26) and is not a heat transfer medium, the components of the support structure 50 are made of much thicker materials than those of the core 20. Unfortunately, these thicker materials cause

the support structure 50 to thermally expand at a much slower rate than the quick responding core 20, with its thin plates 22. The thickness (and thus the thermal response) of the support structure 40 will also be affected by the amount of the pre-load applied to the core 20.

Differential thermal expansion between elements of the heat exchanger 5 will cause a compression load to be applied to the quicker expanding sections (e.g. the core 20 and specifically the stack 26). As noted, a compression load is also applied to the stack 26 by the application of a pre-load. Compressive forces from pre-loading and differential thermal expansion can cause a variety of problems, such as buckling, fatigue failures and creep. Buckling is particularly problematic as it results in the stack 26 expanding outward (laterally) in one or more directions. During this outward expansion the plates 22 separate from one another, resulting in a nearly complete destruction of the heat exchanger.

Fatigue and creep frequently occur when heat exchangers are repeatedly cycled between hot and cold stages. Depending on the particular application, a turbine (not shown) attached to a heat exchanger can be started, ran for a short period of time and then shutdown, over and over. One example of such cyclic use, is a turbine and heat exchanger apparatus employed in the production of electric power. Typically, such devices are run only during recurring periods of peak power demand.

An additional source of loading on the heat exchanger 5 can be from the airflow in the core 20. When the inlet air in the core 20 is pressurized, the core 20 will want to expand out against the support structure 50. This increases the size of support structure needed to contain the core 20, which in turn, further reduces the thermal response of the support structure 50.

Therefore, a need exists for a heat exchanger which accommodates any differential thermal expansion between the core and the supporting structure, thereby preventing core buckling, fatigue failures, creep or other similar problems. The heat exchanger must however apply, throughout the differential expansion, a force (e.g. pre-load) to the core, which is sufficient to keep the core plates from separating or otherwise deviating from their positions. In so doing, the structure of the heat exchanger must be strong enough to carry the high loads

generated by the core without failing. Further, such an apparatus should be relatively simple in construction and operation to minimize its cost, weight and complexity.

SUMMARY

In some embodiments, the present invention provides a heat exchanger which includes a core having a thermally variable size and a support structure. The support structure is connected to the core and thermally deforms to accommodate variations in the size of the core. To minimize, or eliminate, differential thermal expansion between the core and the support structure, the support structure thermally deforms at a rate which is at least similar to the rate of change of the core size. The amount which the support structure deforms is the same, or at least substantially the same, as the thermal variation in the core size.

To achieve such a thermal deformation (expansion and contraction), the support structure employs a thermally deformable member. The thermally deformable member can be a tie rod with a planar center section. The planar section being thin enough to thermally deform (expand and contract) at a rate and an amount, which at least substantially matches that of the rate and amount of size variations of the core. Typically, the support structure has a plurality of tie rods, where each tie rod has a planar section. To improve heat transfer between the tie rods and the gas flow passing them, the planar sections are at least substantially aligned with the gas flow. The support structure can include a first strongback and a second strongback, which are positioned about the core, with the tie rods being mounted between the first and

second strongbacks.

In other embodiments, the present invention is a heat exchanger which has a core and a support structure having a first strongback, a second strongback, and at least one variable thickness tie rod mounted between the strongbacks. Wherein, the support structure receives the core. The core has a first end and an opposing second end. The first strongback is positioned adjacent to the first end of the core and the second strongback is positioned adjacent the second end of the core.

The variable thickness tie rod can have a planar center section, at least one broadened end, or a combination of both. The broadened end tie rod includes a center section and a first end, the first end being thicker (wider) than the center section. The broadened end tie rod can also include a second end which is similarly thicker (wider) than the center section. Preferably, each end has a set of threads which allows the end to receive a fastener (such as a nut) to the secure the tie rod to a strongback. The threads have an inner thread diameter and an outer thread diameter, with the inner thread diameter being at least equal to, or greater, than the thickness of the center section.

The present invention also includes a method of fabricating a tie rod which includes the steps of obtaining a tie rod having a substantially uniform thickness and forging the tie rod to define a planar center section. The forging process includes heating the tie rod and applying pressure to form the planar center section. The method can also include defining threads in an end of the tie rod. In other embodiments, the method has the steps of obtaining a tie rod of uniform thickness, forging a first end of the tie rod to broaden the thickness of the first end, and applying threads to the first end of the tie rod. Applying the threads includes rolling a die over the first end to define the threads. The method can also have the steps of forging a second end of the tie rod to broaden the thickness of the second end, and applying threads to the second end of the tie rod.

BRIEF SUMMARY OF THE DRAWINGS

Fig. 1a is a perspective view of a cross-section of a heat exchanger.

Fig. 1b is a perspective view of a tie rod.

Fig. 1c is a top view of a cross-section of a tie rod.

Fig. 1d is a perspective view of a cross-section of a portion of a tie rod.

Fig. 2 is an isometric view of a turbine/heat exchanger system in accordance with the present invention.

Fig. 3 is an isometric view of a heat exchanger in accordance with the present invention.

Fig. 4 is an angled side cut-away view of a portion of a heat exchanger in accordance with the present invention.

Fig. 5a is a side cut-away view of a portion of a heat exchanger in accordance with the present invention.

Fig. 5b is a perspective view of a tie rod of a heat exchanger in accordance with the present invention.

Fig.s 5c-e are top cross-sectional views of a tie rod of a heat exchanger in accordance with the present invention.

Fig. 6 is a flow chart of a method of fabrication in accordance with an embodiment of the present invention.

Fig. 7a is a side cut-away view of a portion of a heat exchanger in accordance with the present invention.

Fig. 7b is a perspective view of a tie rod of a heat exchanger in accordance with the present invention.

Fig. 7c is a perspective view of a cross-section of a portion of a tie rod of a heat exchanger in accordance with the present invention.

Fig. 8 is a flow chart of a method of fabrication in accordance with an embodiment of the present invention.

Fig. 9a is a perspective view of a tie rod of a heat exchanger in accordance with the present invention.

Fig.s 9b is a perspective view of a portion of a tie rod of a heat exchanger in accordance with the present invention.

Fig.s 9c is a perspective view of a portion of a tie rod of a heat exchanger in

accordance with the present invention.

Fig. 10 is a perspective view of a tie rod of a heat exchanger in accordance with the present invention.

DETAILED DESCRIPTION

The present invention is embodied in both apparatuses and methods of fabrication. The present invention alleviates problems associated with differential thermal expansion between the heat exchanger's core and its support structure. In so doing the Applicants' invention prevents damage to the heat exchanger which would otherwise be caused by buckling, fatigue failure, creep or other similar processes. The invention functions by allowing the support structure to expand at a faster rate and/or by strengthening the support structure sufficiently to accommodate the loads and stresses generated by differential expansion of the core.

Unlike prior structures, the Applicants' invention provides for the relatively fast thermal expansion of the core with a similarly quickly expandable support structure. This is accomplished, in at least some embodiments of the invention, by configuring the tie rods of the support structure so that their temperatures can change rapidly. As detailed below, this is achieved with certain configurations of the tie rods which have sections with increased surface areas and thinner cross-sections. This allows the temperature of the tie rods to change at fast rates.

In addition, the support structure functions to maintain sufficient compression force on the core, to prevent the core from separating or otherwise displacing in an undesired manner. As such, an advantage is achieved with the present invention of minimizing differential thermal expansion, by having the support structure thermally expand at a rate similar to that of the core, while at the same time keeping the core under at least a minimum compressive force (e.g. pre-load).

Various embodiments of the present invention utilize strengthened tie rods which increase the ability of the support structure to carry any loads generated by differential thermal expansion without damage to the heat exchanger structure.

Another advantage of embodiments of the present invention is that by having the support structure and the core expand and contract generally in unison, the support structure and the core are not placed under additional loads which would otherwise be caused by a restraining of the core's movement. As such, the problems of buckling, fatigue failure and creep typically associated with prior heat exchangers are avoided. Further, since the core is not under these additional compressive loads, the pre-load placed on the core can be dramatically reduced. This also allows the heat exchanger to be simpler, lighter and less expensive to manufacture.

Therefore, the present invention provides a heat exchanger, or similar apparatus, which reduces the potential for damage to the core (e.g. plate separation, buckling, fatigue failure, creep, etc.), which is more efficient, easier to manufacture, lighter, and less expensive.

Heat exchanger apparatuses which provide for differential thermal expansion are set forth in U.S. Patent Application No. (To Be Assigned), filed December 21, 2001, entitled HEAT EXCHANGER WITH BIASED AND EXPANDABLE CORE SUPPORT STRUCTURE, by David Beddome, Steve Ayres and Yuhung Edward Yeh, which is hereby incorporated by reference in its entirety; U.S. Patent Application No. 09/652,949, filed August 31, 2000, entitled HEAT EXCHANGER WITH BYPASS SEAL ALLOWING DIFFERENTIAL THERMAL EXPANSION, by Yuhung Edward Yeh, Steve Ayres and David Beddome, which is hereby incorporated by reference in its entirety; and, U.S. Patent Application No. 09/864,581, filed May 24, 2001, entitled HEAT EXCHANGER WITH MANIFOLD TUBES FOR STIFFENING AND LOAD BEARING, by David W. Beddome, Steve Ayres, Yuhung Edward Yeh, Ahmed Hammoud, David Bridgnell and Brian Comiskey, which is hereby incorporated by reference in its entirety.

As shown in Fig. 2, for some embodiments, the present invention is a heat exchanger 100 which can be used in conjunction with a gas turbine engine. The heat exchanger 100 functions to heat the inlet air prior to it entering the turbine and cool the turbine exhaust gases prior to them exiting the heat exchanger 100. This is achieved by directing the inlet air so that it passes adjacent to the exhaust gas, such that heat is transferred from the exhaust to the inlet air. Specifically, as set forth in

Fig. 2, air enters at an air inlet and is directed through the heat exchanger 100 where it is heated by heat from the exhaust gases. Then, the heated air is directed from the heat exchanger 100 to the turbine. The turbine uses the air to operate and in so doing expels the exhaust gas. The exhaust gas is directed into and through the heat exchanger 100 where it heats the inlet air. The cooled exhaust gas then exits from the heat exchanger 100. A detailed description of the functioning and structure of the heat exchanger 100 is set forth herein. While Fig. 2 shows an example of a system in that some embodiments of the present invention are used, many other systems and uses are possible, including the use of engines other than a gas turbine.

Fig. 3 shows an embodiment of the heat exchanger 100 with an air inlet 114 and an air outlet 118, to bring air into and out of a heat transfer core (not shown), and an exhaust gas inlet and an exhaust gas outlet, to direct the exhaust gases through the heat exchanger 100. The heat exchanger 100 also has a shell assembly 160 with a first or upper strongback 143 and a second or lower strongback 145 (not shown) on either end. Connecting the strongbacks are a set of tie rods 150. Fig. 3 also sets forth the cross-sections of the heat exchanger 100 as shown in Fig.s 4 and 5a.

For some embodiments of the present invention, as shown in the cut-away views of Fig.s 4 and 5a, the heat exchanger 100, has a core 110 positioned within the shell assembly 160. Outside the shell 160 are the upper strongback 143 and the lower strongback 145, connected by the tie rods 150a.

The core 110 is positioned within the shell 160. The core 110 functions to duct the inlet air pass the exhaust gas, so that the heat of the exhaust gas can be transferred to the cooler inlet air. The core 110 performs this function while keeping the inlet air separated from the exhaust gas, such that there is no mixing of the air and the gas. By moving air near the gas without mixing the two, the heat exchanger 100 transfer heat at a high level of efficiency. Further, the heat exchanger 100 also maximizes engine performance by not allowing the exhaust gases to be introduced into the intake air of the turbine (or other engine).

As shown in Fig.s 4 and 5a, the core 110 has an exterior surface 112. An air inlet 114 and an air outlet 118 to bring air into and out of the core 110. The air inlet

114 receives relatively cool inlet air for passage through the core 110. When the heat exchanger 100 is operating, the air exiting the air outlet 118, having been heated in the core 110, will have a much higher temperature than the inlet air. Between the air inlet 114 and the air outlet 118 are the inlet manifold 116, a heat exchange region 122 and the outlet manifold 120.

While the heat exchanger 100 is operating, the core 110 has a variable size (e.g. length) caused by thermal expansion or contraction. That is, as the core 110 is heated up by the exhaust gases passing through the shell, the core 110 will expand and as the heat exchanger 100 stops operating the core 110 will contract as it cools.

The heat exchange region 122 can be any of a variety of configurations that allow heat to transfer from the exhaust gas to the inlet air, while keeping the gases separate. However, it is preferred that the heat exchange region 122 be a prime surface heat exchanger having a series of layered plates 128, which form a stack 130. The plates 128 are arranged to define heat exchange members or layers 132 and 136 which alternate from ducting air, in the air layers 132, to ducting exhaust gases, in the exhaust layers 136. These layers typically alternate in the core 110 (e.g. air layer 132, gas layer 136, air layer 132, gas layer 136, etc.). Separating each layer 132 and 136 is a plate 128.

On either end of the stack 130 are a first end plate 142 and a second end plate 144. The first end plate 142 is positioned against the upper portion of the shell assembly 160 and the second end plate 144 is positioned against the lower portion of the shell assembly 160.

Also shown in Fig. 5a, are the ties rods 150a positioned on either side of the core 110. A series of the tie rods 150a and an upper strongback or load bearing member 143 and a lower strongback or load bearing member 145, are used to hold the stack 130 together and carry loads. The tie rods 150a function to apply a compressive load to the strongbacks 143 and 145. The tie rods 150a include a center section 151a running between either end 152a and fasteners 154a at each end 152a. The fasteners 154a function to hold the tie rods 150a to the strongbacks 143 and 145. The ends 152a have a set of threads 153a which are received by the fasteners 154a. The tie rods

150a can be made of any suitable well known material including, but not limited to, steel and aluminum. However, the tie rods 150a are preferably stainless steel. The tie rods 150a are described in further detail below.

On the outside of the shell 160 and above and below the core 110, are the upper strongback 143 and the lower strongback 145. The tie rods 150a and the strongbacks 143 and 145 (as well as the shell 160) carry compressive loads applied to the stack 130. These compressive loads can be from a variety of sources including pre-loading, differential thermal expansion, air pressure, and the like.

The upper strongback 143, the lower strongback 145, the tie rods 150a, and the shell 160, collectively form a support structure 170a. The support structure 170a functions to apply the compressive force to the stack 130 of the core 110. In contrast to the tie rods 150a, the upper strongback 143 and the lower strongback 145 (collectively a fixed member, with the upper strongback 143 a first portion of the fixed member and the lower strongback 145 a second portion of the fixed member) are generally not deformable.

As can be seen, the plates 128 are generally aligned with the flow of the exhaust gas through the shell assembly 160. The plates 128 can be made of any well known suitable material, such as steel, stainless steel or aluminum, with the specific material dependent on the operating temperatures and conditions of the particular use. The plates 128 are stacked and connected (e.g. welded or brazed) together in an arrangement such that the air layers 132 are closed at their ends 134. With the air layers 132 closed at ends 134, the core 110 retains the air as it passes through the core 110. The air layers 132 are, however, open at air layer intakes 124 and air layer outputs 126. As shown in Fig.s 4 and 5a, the air layer intakes 124 are in communication with the inlet manifold 116, so that air can flow from the air inlet 114 through the inlet manifold 116 and into each air layer 132. Likewise, the air layer outputs 126 are in communication with the outlet manifold 120, to allow heated air to flow from the air layers 132 through the outlet manifold 120 and out the outlet 118.

In contrast to the air layers 132, the gas layers 136 of the stack 130 are open on each end 138 to allow exhaust gases to flow through the core 110. Further, the gas

layers 136 have closed or sealed regions 140 located where the layers 136 meet both the inlet manifold 116 and the outlet manifold 120. These closed regions 140 prevent air, from either the inlet manifold 116 or the outlet manifold 120, from leaking out of the core 110 into the gas layers 136. Also, the closed regions keep the exhaust gases from mixing with the air.

Therefore, as shown in Fig.s 4 and 5a, the intake air is preferably brought into the core 110 via the inlet manifold 116 and distributed along the stack 130, passed through the series of air layer intakes 124 into the air layers 132, then sent through the air layers 132 (such that the air flows adjacent - separated by plates 128 - to the flow of the exhaust gas in the gas layers 136), exited out of the air layer 132 at the air layer outputs 126 into the outlet manifold 120, and finally out of the core 110. In so doing, as the air passes through the core 110, it receives heat from the exhaust gas.

With the stack 130 arranged as shown in Fig.s 4 and 5a, the hot exhaust gas passes through the core 110 at each of the gas layers 136. The exhaust gas heats the plates 128 positioned at the top and bottom of each gas layer 136. The heated plates 128 then, on their opposite sides, heat the air passing through the air layers 132.

As the plates 128 and the connected structure of the core 110 heat up, they expand. This results in an expansion of the entire stack 130 and thus of the core 110. As noted in detail below, the support structure 170a is configured to thermally expand at a rate similar to, or equal to, the thermal expansion of the core 110. In this manner, the support structure 170a allows the core 110 to expand without the build-up of excessive forces between the core 110 and the support structure 170a. This prevents the core 110 from being damaged by the compressive forces which would otherwise be created if the support structure did not thermally expand with the core 110. In addition, in at least some embodiments, the support structure 170 continuously applies to the core 110 a compressive force which is at least sufficient to keep the core 110 from buckling or the plates 128 from being displaced.

Although the core 110 can be arranged to allow the air to flow through it in any of a variety of ways, it is preferred that the air is channeled so that it generally flows in a direction opposite, or counter, to that of the flow of the exhaust gas in the

gas layers 136 (as shown in the cross-section of Fig. 5a). With the air flowing in an opposite direction to the direction of the flow of the exhaust gas, it has been found by the Applicants that the efficiency of the heat exchanger is significantly increased as compared to other flow configurations.

The arrangement of the core 110 can be any of a variety of alternate configurations. For example, the air layers 132 and gas layers 136 do not have to be in alternating layers, instead they can be in any arrangement which allows for the exchange of heat between the two layers. For example, the air layers 132 can be defined by a series of tubes or ducts running between the inlet manifold 116 and the outlet manifold 120. While the gas layers 136 are defined by the space outside of, or about, these tubes or ducts.

To facilitate heat transfer, the core 110 can also include secondary surfaces such as fins or thin plates connected to the inlet air side of the plates 128 and/or to the exhaust gas side of the plates 128.

The core 110 and shell 160 can carry various gases, other than, or in addition to, those mentioned above. Also, the core 100 and shell 160 can carry any of a variety of fluids.

As shown in Fig.s 4 and 5a, the shell assembly includes side walls 162, openings 164, an upper panel 166 and a lower panel 168. The shell assembly 160 functions to receive the hot exhaust gases, channel them through the core 110, and eventually direct them out of the shell 160. The shell 160 is relatively air tight to prevent the exhaust gases from leaking out of the shell 160. The shell 160 is large enough to fully contain the core 110 and at least strong enough to withstand the pressure exerted on the shell 160 by the exhaust gas. Typically, the shell 160 is somewhat flexible and can be deformed to varying amounts depending on its specific construction.

The openings 164 of shell 160 are positioned through the upper panel 166. The shell assembly 160 can be made of any suitable well known material including, but not limited to, steel and aluminum. Preferably, the shell 160 is a stainless steel.

The construction of the shell assembly 160 can vary depending on the particular embodiment of the present invention. In some embodiments the shell 160 is constructed to carry some of the compressive load generated by the support structure 170a and applied to the core 110. The shell 160 can also be configured to carry other internally created loads (e.g. air pressure loads) and externally exerted loads (e.g. inertia loads or vibration loads). Because in some embodiments of the present invention, the walls 162, upper panel 166 and lower panel 168 of the shell 160 are thick relative to the thin core plates 128, the shell 160 will thermally expand at a slower rate than the core 110. This can result in differential thermal expansion or contraction between the shell 160 and the core 110, as the two are either heated or cooled, as the case may be. To avoid, or to minimize, gaps or spaces forming between the core 110 and the shell 160 during differential expansion, the shell 160 is flexible enough to be deformed by the forces applied by the strongbacks 143 and 145 and the tie rods 150a.

In other embodiments, the structure of the shell 160 is relatively thin. In such embodiments, the compressive loads created by the support structure 170a are primarily carried by the strongbacks 143 and 145 and the tie rods 150a. In such embodiments, because the shell 160 is thinner, the shell 160, thermally expands and contracts much quicker. This allows any differential thermal expansion between the shell 160 and the core 110 to be minimized. Which, in turn, aids in preventing gaps from forming between the core 110 and the shell 160. This thinner structure also increases the shell's flexibility and allows the shell 160 to be more easily deformed by the strongbacks 143 and 145 and the tie rods 150a. As such, in these embodiments, the potential for exhaust gases being able to pass around the core 110, through gaps between the core 110 and the shell 160, is further reduced.

The present invention, however, provides for differential thermal expansion between the structures of the heat exchanger 100 by employing a support structure 170a which has a thermal response rate similar, or equal, to that of the core 110. As shown herein, a variety of embodiments of the support structure and tie rods exist.

Tie Rods with Planar Center Sections:

One embodiment of the present invention is shown in Fig.s 5a-c. As can be seen in Fig. 5a, the heat exchanger 100 has a support structure 170a which includes the tie rods 150a. Each tie rod 150a has a flat or planar section 151a positioned between each end 152a of the tie rods 150a. The planar section 151a functions to allow the tie rod 150a to expand and contract at a relatively fast rate. This in turn, allows the support structure 170a, as a whole, to thermally expand and contract at a rate which is at least similar to that of the core 110. With it being preferred that the support structure 170a and the core 110 expand and contract at substantially the same rate.

The planar section 151a gives the tie rod 150a a significantly greater overall surface area than is provided by the tie rod 30 which has a round center section 31, as shown in Fig.s 1a-c. Returning to Fig.s 5a-c, the greater surface area of the planar section 151a, increases the heat transfer rate to and from the tie rod 150a and the air surrounding it. In other words, by employing the planar section 151a, the tie rod 150a transfers heat between itself and the exhaust gases flowing past it, at a faster rate than the round shaped tie rod 30 (shown in Fig.s 1a-c). Therefore, the tie rod 150a has a faster thermal response to changes in the temperature of the exhaust gases passing around it.

The planar section 151a also provides a substantially reduced thickness for the cross-section of the tie rod 150a. That is, as compared to the thickness, T_r, of the cross-section of the round tie rod 30 (shown in Fig.s 1a-c), the planar section 151a has a much smaller thickness, T_a. As a result, the internal portion of the planar section 151a can change its temperature much quicker than the internal portion of the thicker round tie rod 30. Therefore, the reduced thickness of the planar section 151a increases the thermal response of the tie rod 150a. Also, as noted in detail below, the reduced thickness of the cross-section reduces the resistance to the flow past the tie rod 150a, resulting a lower pressure drop across the core 110.

Although the tie rod 150a has a cross-section with a thinner thickness, T_a, than that of the round tie rod 30, it has sufficient width, W_a, to maintain a cross-sectional

area similar to, or the same as, that of the round tie rod 30. With a similar cross-sectional area, the tie rod 150a can carry axial tension loads which are the same, or at least very close to, those carried by the round cross-section tie rod 30. That is, the tie rod 150a by having more surface area and being thinner, has a faster thermal response than a round tie rod. However, by keeping at least a similar total cross-sectional area, the tie rod 150a can carry the same loads carried by a rounded tie rod.

Therefore, as an engine, such as a gas turbine (not shown), attached to the heat exchanger changes its operating condition (starts up, shuts down or the like), the tie rods 150a allow the support structure 170a to expand or contract along with the core 110, as their temperatures change. Specifically, as the temperature of the exhaust gas changes, the plates 128 of the core 110 will expand or contract, resulting in a lengthening or shortening (respectfully) of the entire core 110. Likewise, the change in the exhaust gas temperature will heat or cool the planar section 151a of the tie rod 150a, causing the tie rod 150a to lengthen or shorten (respectfully). The lengthening or shortening of the tie rods 150a cause the support structure 170a, as a whole structure, to expand or contract.

While the tie rods 150a can be designed to expand or contract at any of a variety of rates relative to the thermal response of the core 110, it is preferred that the thermal response of the tie rods 150a is the same as, or substantially the same as, that of the core 110. In this manner, expansion or contraction of the support structure 170a will exactly, or substantially, match that of the core 110. The result being that the differential expansion or contraction between the core 110 and the support structure 170a is eliminated or at least minimized. In so doing, loads created by differential expansion or contraction are likewise eliminated or minimized.

As shown in Fig.s 5a-c, the tie rods 150a are positioned with the planar sections 151a aligned with the flow of the exhaust gases passing through the shell 160. In this position, the exhaust gases flow evenly around both sides of the planar section 151a, aiding heat transfer between the gases and the tie rods 150a. With the exhaust gases flowing along the planar sections 151a, the rate of heat transfer between the gases and the tie rods 150a is maximized. As a result, the thermal expansion or contraction of the tie rods 150a are at least close to that of the core 110. Of course, it

is preferred that the rate of the thermal expansion and contraction of the tie rod 150a is substantially similar to, or the same as, that of the core 110. With such matched expansion and contraction rates, the amount of differential thermal expansion or contraction (if any) between the support structure 170a and the core 110 is minimized.

With the planar sections 151a of the tie rods 150a aligned with the flow of the exhaust gases, any obstruction of the gas flow by the tie rods 150a is minimized. This reduces the about of air drag of the gases through the shell 160, increasing the overall efficiency of the turbine/heat exchanger system. Although it is preferred that the planar sections are aligned with the flow of the exhaust gases, in other embodiments of the present invention, one or more of the tie rods are orientated so that the planar sections are angled relative to the gas flow. The angling of the planar sections can be used to direct the gas flow for improved flow distribution across the face of the core 100 and to improve the overall performance of the heat exchanger 100.

The embodiment of the invention, as shown in Fig.s 5a-c, has the planar section 151a running along substantially the entire length of the tie rod 150a. However, in other embodiments of the present invention, the length of the planar section is shorter or longer. In some embodiments, there is more than one planar section. The specific length of the planar section 151a of the tie rod 150a is dependent on the desired rate of thermal expansion for the particular design of the heat exchanger. That is, the greater the rate of thermal expansion of the tie rods 150a which is needed to match the rate of the core 110, the longer the planar section 151a will be.

In other embodiments of the heat exchanger 100, the configuration of the planar sections of different tie rods can vary, such that the tie rods expand and contract at separate rates. Such embodiments allow the expansion or contraction of the tie rods to be set match any non-uniform expansion or contraction of the core. Also, these embodiments allow the tie rods to maintain a substantially uniform expansion or contraction rate even with non-uniform heating or cooling of the tie rods.

While the surface area and thermal response of the tie rod 150a can be

maximized by minimizing the thickness, T_a, and increasing the width, W_a, it is preferred that the shape and the size of the planar section 151a of each tie rod 150a is set so that the tie rod 150a is stiff enough to prevent, or at least minimize, any vibrations and/or flutter of the tie rod 150a caused by the flow of the exhaust gases past the tie rod 150a.

One skilled in the design of such structures, using well known analytical and/or empirical methods, can determine the specific configuration of the planar section 151a to accommodate each particular design and use of the heat exchanger 100.

In at least one embodiment of the present invention the tie rod 150a has only one end which includes the threads 153a and the fastener 154a, while the other end is simply formed (or shaped) to be restrained by the strongback which it is in contact with. For example, this end can be flared out so that it is restrained by the strongback. Such embodiments still allows the tie rod 150a to be tightened down by the fastener 154a and threads 153a, but since both end do not need to have the threads 153a and the fastener 154a, the cost of manufacturing is lowered.

In some embodiments of the present invention, the cross-section of the planar section 151a of the tie rod 150a varies from that shown in Fig. 5c. The cross-section of the planar section 151a can be any shape which allows the tie rod 150a to maintain a sufficiently fast thermal response rate. Examples of other cross-section shapes are shown in Fig.s 5d and e.

The tie rod 150a can be fabricated by any of a variety of methods well known to those skilled in the art including forging, casting, extruding, milling, etching, welding and the like. However, it is preferred that the tie rod 150a is formed by hot forging a tie rod with a rounded cross-section to create the planar section 151a.

In some embodiments of the present invention, a method 200 can be used to fabricate the tie rod 150a. The method 200 is set forth in the flow chart of Fig. 6. As shown, the method 200 includes the steps of obtaining a tie rod of uniform thickness 210 and forging the center section of the tie rod to define a planar shape 220. The

method 200 can be repeated to various sections of the tie rod 150a, to create the planar section 151a in steps and/or to create more than one planar surface.

The step of obtaining a tie rod of uniform thickness 210, preferably includes starting with a rounded (blank) tie rod (such as tie rod 400 shown in Fig. 9a) which has a substantially uniform thickness. The tie rod can be any of a variety of suitable materials including, steel and aluminum. However, it is preferred that a stainless steel is used.

The step of forging the center section of the tie rod to define a planar shape 220 preferably includes enlarging the width of the tie rod until a desired size is reached. Specifically, that the center section of the uniform width tie rod is heated until it can be formed or shaped to a greater width and lesser thickness than that of the rounded tie rod. That is, after being heated, a force is applied to the center section to widen and thin the center section into a planar shape, such as the shape of the tie rod 150a as shown in Fig. 5b. The specific temperature which the rounded tie rod is heated to before shaping is dependent on the material of the tie rod.

<u>Tie Rods with Broadened Ends</u>:

As shown in Fig.s 7a-c, some embodiments of the present invention have a support structure 170b with enlarged end tie rods 150b which are capable of carrying increased loads. This allows the support structure 170b to react to greater loads caused by either differential thermal expansion or contraction of the core 110 and the support structure 170b, pre-loading of the core 110 by the support structure 170b, internal pressurization of the core 110, or any other sources. The tie rods 150b also reduce the potential for damage to the support structure 170b, which would otherwise result from failure of one or more uniform width tie rods.

The tie rods 150b have ends 152b which are enlarged as compared to those of the uniform width tie rods 30, as shown in Fig.s 1a-d. Returning to Fig.s 7a-c, it can be seen that the ends 152b have threads 153b which are positioned about the rim of each end 152b. The threads 153b function to receive the threads of the fastener or bolt 154b. In this manner, the tie rod 150b can be held in place against either the

upper strongback 143 or the lower strongback 145.

As shown in Fig. 7c, the threads 153b have an inner diameter, D_{bi}, and an outer diameter, D_{bo}. As can be seen, in Fig.s 1d and 7c, both the diameters, D_{bi}, and D_{bi}, of the broadened end tie rod 150b are, relative to the central rod thickness, T_b, proportionally larger that the thread diameters, D_{ri}, and D_{ri}, and rod thickness, T_r, of the uniform rounded tie rod 30. As such, the tie rod 150b has a proportionally larger contact area, A_b, between the threads 153b of the tie rod 150b and the threads 155b of the fastener 154b. For one turn of the thread, the area, A_b, is determined by the formula:

$$A_b = \Pi[(D_{bo}/2)^2 - (D_{bi}/2)^2]$$

As can be seen by the above formula, the total contact area is related exponentially to the difference in the outer and inner thread diameters. The total load which can be carried by the threads 153b is in turn directly related to the contact area, A_b. In other words, by placing the threads 153b further out from the center of the tie rod 150b, a significant increase is obtained in the load which the tie rod 150b can carry.

To further increase the contact area, and thus the load which can be carried by the tie rod 150b, several turns of the threads 153b are used.

By increasing the total contact, A_b, of the tie rods 150b, the stress concentrations at the threads, for a given load on the tie rod 150b, are reduced.

The specific dimensions and number of the threads 153b of the tie rod 150b can vary depending on the requirements of the particular use which the tie rod 150b is employed. With information such as expected tie rod loading, material properties of the tie rods and the like, one skilled in the art can determine the desired dimensions (inner and outer thread diameters, number of turns, tie rod head size, and the like) by using well known analytical and/or empirical methods.

While the width of the inner diameter, D_{bi}, and the outer diameter, D_{bo}, of the

threads 153b can vary, as noted in detail above, it is preferred that the inner diameter, D_{bi}, is equal to, or larger than, the central rod thickness, T_b.

In at least one embodiment of the present invention the tie rod 150b has only one end which includes the threads 153b and the fastener 154b, while the other end is simply formed (or shaped) to be restrained by the strongback which it is in contact with. For example, this end can be flared out so that it is restrained by the strongback. Such embodiments still allows the tie rod 150b to be tightened down by the fastener 154b and threads 153b, but since both end do not need to have the threads 153b and the fastener 154b, the cost of manufacturing is lowered.

The tie rods 150b can be fabricated by a variety of methods. One such method 300 is set forth in the flow chart of Fig. 8. As shown, the method 300 includes the steps of obtaining a tie rod of uniform thickness 310, forging an end of the tie rod 320 and applying threads to the end of the tie rod 330. This method 300 can be repeated to the other end of the tie rod, such that both ends are forged and have threads applied to them.

The step of obtaining a tie rod of uniform thickness 310, preferably includes providing a round blank tie rod 400 which has a substantially uniform thickness, T_x, as shown in Fig. 9a. The blank tie rod 400 can be any of a variety of suitable materials including, steel and aluminum. However, it is preferred that a stainless steel is used. As can be seen, at this stage in the method 300 the blank tie rod 400 lacks threads. In order to provide sufficient material for the later enlargement of ends of the tie rods, it is preferred that the tie rod 400 is longer than necessary to connect between the upper and lower strongbacks of the heat exchanger. The specific additional length depending on the desired width and length of the enlarged ends of the finished tie rods.

The step of forging an end of the tie rod 320 preferably includes enlarging the end of the tie rod until a desired diameter is reached. Specifically, that an end 402 of the uniform width tie rod 400 is heated until the end 402 can be formed or shaped to a larger diameter. That is, after being heated, a force is applied to the end 402 to shorten and broaden the end 402. Such a tie rod 410 having an broadened end 412 is

shown in Fig. 9b. The specific temperature which the end 402 is heated to before shaping, is variable and dependent on the material of the tie rod 400.

One skill in the art of forging and forming will recognized that processes and equipment similar to that used to make the heads on bolts can be employed to create the enlarged head 412 on the tie rod 410.

It should be further noted that the broadened end 412 of the tie rod 410 can be created by a variety of methods other than forging. Such alternate methods include casting, milling, lathing, welding and the like. The tie rod 410 can also be shaped as described above but without the heating of forging.

The step of applying threads to the end of the tie rod 330 preferably includes taking the tie rod 410 and rolling threads on to an edge 414 of the end 412 of to create the tie rod 420, as shown in Fig. 9c. The tie rod 420 having on the edge 424 of an end 422 a set of threads 426. During this step a die (not shown), shaped in the reverse of the threads 426, is moved over the surface of the edge 414 under pressure to define the threads 426. To aid in the deformation of the end 412, the application of the die is preferably done while end 412 is still heated. Alternatively, the end 412 can be rolled across a fixed die under pressure to apply the threads 426.

While it is preferred to roll the threads 426 onto the end 412 of the tie rod 410, the threads 426 can be applied by a variety of other methods. Such methods include casting, milling, lathing or etching to define the threads and/or welding or use of an adhesive to attach a structure having the threads.

It should be clear to one skilled in the art that either one or both ends of a tie rod can be enlarged and have threads. Also, that the shape of each enlarged end can vary. For example, as shown in Fig.s 7b and c, the end 152b has a tapered portion 156b which aids in the reduction of stress concentrations on the tie rod 150b.

Combined Planar Section and Broadened Ends Tie Rod:

As shown in Fig. 10, in another embodiment of the present invention, a tie rod

150c includes both a planar center section 150c and enlarged ends 152c. The tie rod 150c incorporates the functioning and configuration of the planar section 151a of the tie rod 150a, and the enlarged ends 152b of the tie rod 150c, as set forth in detail above. That is, the tie rod 150c includes the planar section 151c so that the tie rod 150c can thermally respond at rate which is near to, or equal to, that of the core 110 (not shown), and has the enlarged ends 152c so that the tie rod 150c can carry increased loads. The tie rod 150c further includes threads 153c which are shaped to receive the threads of a fastener (not shown) as well as a tapered section 156c and round sections 157c.

Object.

In at least one embodiment of the present invention the tie rod 150c has only one end which includes the threads 153c and the fastener 154c (not shown), while the other end is simply formed (or shaped) to be restrained by the strongback which it is in contact with. For example, this end can be flared out so that it is restrained by the strongback. Such embodiments still allows the tie rod 150c to be tightened down by the fastener 154c and threads 153c, but since both end do not need to have the threads 153c and the fastener 154c, the cost of manufacturing is lowered.

While the preferred embodiments of the present invention have been described in detail above, many changes to these embodiments may be made without departing from the true scope and teachings of the present invention. The present invention, therefore, is limited only as claimed below and the equivalents thereof.